Rateless Code Based Multimedia Multicasting with Outage Probability Constraints

Wei Sheng, Wai-Yip Chan and Steven D. Blostein
Queen's University, Kingston, Canada

Abstract— **An unequal error protection (UEP) transmission scheme is proposed for multimedia multicasting systems employing a priority encoding transmission (PET)-based packetization structure [1] combined with rateless codes. Outage probability is analyzed for the layered multicast framework. A novel transmission scheme is proposed which is capable of minimizing the transmission cost while simultaneously guaranteeing outage probability constraints. Simulation results show that our proposed transmission scheme performs well in a multicasting system with transmission deadlines and asynchronous access start times.**

I. INTRODUCTION

There is an increasing push to move toward multicast, which allows the deployment of multimedia applications over lossy packet networks while minimizing their demand for bandwidth [2]. Multicasting of scalable image and video to heterogenous receivers calls for unequal error protection (UEP).

Recently, UEP schemes based on rateless codes have been proposed due to their simple encoding and decoding algorithms and capabilities to adapt to channels with uncertain parameters. The existing rateless-codes-based UEP schemes either non-uniformly choose message bits [3], or employ Expanding Window Fountain (EWF) codes [4] to provide protection for scalable image and video contents. The above mentioned schemes, however, do not consider guaranteed user experience.

To address the above problem, in this paper, we propose a quality-of-service (QoS)-aware UEP transmission scheme. In a practical system, multimedia contents are grouped into a sequence of group of frames (GOF), and each GOF can only be transmitted within a certain time period due to real-time delay constraints and limited system resources. Therefore, the system can only transmit a certain maximum number of packets, which corresponds to a *cutoff deadline*. Late-tune-in receivers or receivers with poor channel conditions may not achieve their target QoS when the cutoff deadline is reached, leading to a non-negligible outage probability.

In this paper, we analyze the outage probability for layered multicast packetization structures, and then discuss how to allocate source bits to rateless coded packets to satisfy outage probability constraints. After that, a novel allocation scheme is proposed which minimizes the average transmission cost while simultaneously satisfying heterogeneous outage constraints.

We remark that in a previous work [5], we have investigated the transmission scheme for systems without a cutoff deadline, in which ultimately each receiver can reach its target QoS with zero outage probability. The proposed scheme in this paper is an extension of [5] to a more realistic multicasting scenario.

The rest of this paper is organized as follows: Section II describes the system model; Section III discusses the outage probability for a given allocation scheme; Section IV provides a novel bit-to-packet allocation scheme for systems with restricted numbers of transmitted packets; Section V presents the simulation results.

II. SYSTEM DESCRIPTION

In this paper, we investigate a multimedia multicasting system where an embedded source bit stream is transmitted from a server to a number of heterogenous receivers.

There are J classes of receivers, and the number of receivers in class j is denoted by M_j. Each class is characterized by a QoS requirement in terms of a target peak signal-to-noise ratio (PSNR) of the reconstructed signal, denoted by γ_j for class j, $j = 1, .., J$. In the proposed scheme, PSNR can be straightforwardly replaced by other measures of source reconstruction quality.

We consider a network with memoryless and independent packet erasure channels, in which the actual erasure rate for a receiver is not known precisely, but the set of all possible channel erasure rates as well as their probabilities are known at the transmitter. The channel erasure rate for receiver i in class j, denoted by $\rho_{j,i}$, where $i = 1, .., M_j$ and $j = 1, .., J$, can be chosen from a set of possible channel erasure rates, $\mathbf{h}_j = \{h_{j,1}, .., h_{j,b_j}\}$, where b_j denotes the size of this set, with probabilities $\mathbf{p}_j = \{p_{j,1}, .., p_{j,b_j}\}$. Once the channel erasure rate is chosen, it remains unchanged during the whole transmission period.

At the transmitter/server, to mitigate the channel errors, the source bit stream is loaded onto a sequence of packets by a PET-like layered packetization structure, as illustrated in Figure 1. The number of layers, denoted by L, is equal to the packet size, and the number of allocated source bits for layer i is denoted by K_i, where $i = 1, .., L$. A lower-indexed layer contains more significant source symbols than a higher-indexed layer.

With layered packetization, a sequence of packets can then be transmitted to receivers until all receivers' QoS requirements are satisfied, or a cutoff deadline, N_{max}, is reached. Here N_{max} is given by the system which depends on delay and resource considerations.

To accommodate the asynchronous receivers, which start receptions at time instances they choose, we introduce the concept of an *access window*, which is defined as the time interval over which receivers can initiate access to the multicast. Throughout this paper, a time interval is represented by indices of the transmitted packets. The access window for class j, denoted by $[1, I_{cut,j}]$, implies that any class j receiver can access the system at a time instance between the first transmitted packet and the $I_{cut,j}$-th transmitted packet. We assume that the access start time instances of receivers in class j have independent uniform distributions within the access window of $[1, I_{cut,j}]$. Outside this window, although receivers can still start their receptions, the QoS is not guaranteed. In this paper, the transmission scheme is designed by only considering the receivers which access the system within the access window.

III. OUTAGE ANALYSIS

Due to the cutoff limit, N_{max}, there exists a non-zero outage probability for each receiver, defined as the probability that a target QoS cannot be satisfied after all N_{max} packets have been sent. In this section, we evaluate the outage probability.

---

[1] This work was supported by Natural Sciences and Engineering Council of Canada Strategic Project Grant STPSC 356826-07.

978-1-4244-5711-3/10/$26.00 ©2010 IEEE

Authorized licensed use limited to: Queens University. Downloaded on July 05,2010 at 17:03:36 UTC from IEEE Xplore. Restrictions apply.

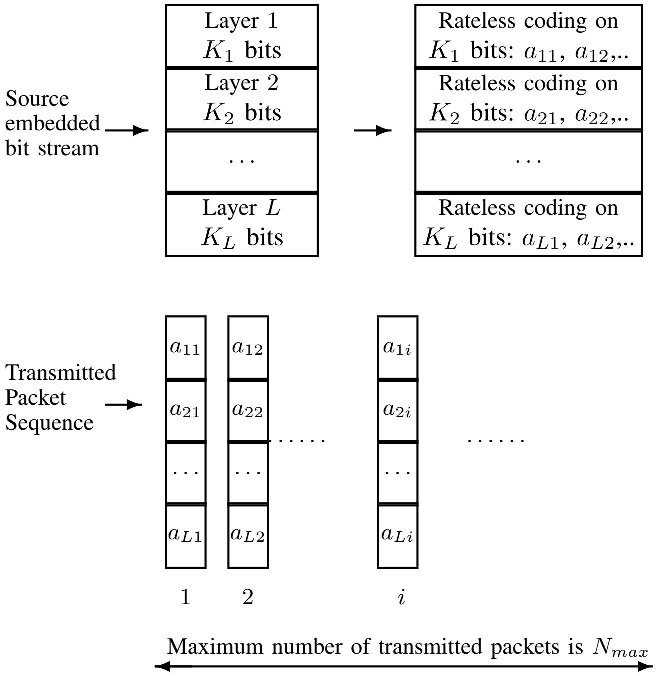

Fig. 1. Layered packetization structure combined with rateless codes.

A. QoS constraints

Without loss of generality, the J classes are ordered with increasing target PSNR, i.e., $\gamma_1 \leq \gamma_2 \leq .. \leq \gamma_J$. In the course of compressing a source, its operational rate-distortion function (e.g., in terms of PSNR versus number of decoded source bits) can be obtained, denoted by $f(.)$. Therefore, to achieve a target PSNR γ_j, where $j = 1, .., J$, at least R_j source bits must be successfully decoded,

$$R_j = f^{-1}(\gamma_j) \tag{1}$$

where f^{-1} denotes the inverse of the operational rate-distortion function.

Each receiver can keep receiving packets, and then decode the source symbols layer by layer. After one layer is successfully decoded, the receiver evaluates its current PSNR, and then decides if it is necessary to receive more packets. Therefore, for class j, the number of successfully decoded layers, denoted by d_j, determines the received PSNR, denoted by $\text{PSNR}_j(K_1, .., K_L)$. Therefore, to ensure a target PSNR, d_j should be chosen to satisfy the following condition

$$\begin{aligned} \text{PSNR}_j(K_1, .., K_L) &= f(\sum_{m=1}^{d_j} K_m) \\ &\geq \gamma_j. \end{aligned} \tag{2}$$

With an embedded source bit stream, the less important bits are not usable if the preceding more important bits are not correctly received. Therefore, the more important part of the source stream should be better protected. Since layer i is useless if layers $1, \ldots, i-1$ are not decoded successfully, layer $i-1$ should have no less error protection than layer i, i.e., the channel code rate of layer $i-1$ is no greater than that of layer i. This is accomplished by setting

$$K_1 \leq K_2 \leq .. \leq K_{L-1} \leq K_L. \tag{3}$$

With rateless codes, it is assumed that $K_l(1+\delta_l)$ received packets are required to successfully decode the l^{th} layer, where δ_l represents the fraction of overhead needed to recover layer l, and is dependent on the rateless code design. As shown in (2), to satisfy the target QoS requirement for class j, at least d_j layers should be decoded. Therefore, $\ulcorner K_{d_j}(1+\delta_{d_j})\urcorner$ packets should be collected at a class j receiver to achieve QoS, where $\ulcorner a \urcorner$ denotes the smallest integer larger than or equal to a.

B. Outage probability for a specific receiver

For a given user i in class j, under the assumption that all packets are erased independently with erasure rate of $\rho_{j,i}$, the probability that n packets are correctly received after all N_{max} packets are transmitted, can be expressed as follows

$$P_{n,N_{max}} = \binom{N_{max} - I_{j,i} + 1}{n} (1-\rho_{j,i})^n \rho_{j,i}^{N_{max} - I_{j,i} + 1 - n}$$

where $I_{j,i}$ denotes the access start time for receiver i.

The outage probability for user i in class j, denoted by $P_{out}^{j,i}$, can thus be expressed as the probability that less than $\ulcorner K_{d_j}(1+\delta_{d_j})\urcorner$ packets are correctly received after all N_{max} packets have been transmitted,

$$\begin{aligned} P_{out}^{j,i} &= \sum_{n=0}^{\ulcorner K_{d_j}(1+\delta_{d_j})\urcorner - 1} P_{n,N_{max}} \\ &= \sum_{n=0}^{\ulcorner K_{d_j}(1+\delta_{d_j})\urcorner - 1} \binom{N_{max} - I_{j,i} + 1}{n} (1-\rho_{j,i})^n \times \\ &\quad \rho_{j,i}^{N_{max} - I_{j,i} + 1 - n}. \end{aligned}$$

C. Average outage probability

The average outage probability for class j can then be obtained by

$$P_{out,j}^{av} = \frac{1}{M_j} \sum_{i=1}^{M_j} P_{out}^{j,i}. \tag{4}$$

The above equation is a function of channel erasure rate $\rho_{j,i}$ and access start time $I_{j,i}$, where $i = 1, .., M_j$. As mentioned previously, $I_{j,i}$ is uniformly distributed over the access window, and $\rho_{j,i}$ can be randomly chosen from a set of possible channel erasure rates. Therefore, if M_j is moderately large, e.g., $M_j \geq 30$, by the Weak Law of Large Numbers (WLLN), the above equation can be approximated by

$$\begin{aligned} P_{out,j}^{av} &\approx E_{I_{j,i},\rho_{j,i}}[P_{out}^{j,i}] \\ &= \sum_{d=1}^{b_j} p_{j,d} \sum_{m=1}^{I_{cut,j}} \frac{1}{I_{cut,j}} \sum_{n=0}^{\ulcorner K_{d_j}(1+\delta_{d_j})\urcorner - 1} \\ &\quad \binom{N_{max} - m + 1}{n} (1-h_{j,d})^n h_{j,d}^{N_{max} - m + 1 - n} \end{aligned} \tag{5}$$

where $E_{a,b}[g]$ indicates the expectation of g taken with respect to random variables a and b; $h_{j,m}$ and $p_{j,m}$, $m = 1, .., b_j$, denote a possible erasure rate and its corresponding selection probability, respectively.

Authorized licensed use limited to: Queens University. Downloaded on July 05,2010 at 17:03:36 UTC from IEEE Xplore. Restrictions apply.

D. Worst-case outage probability

Worst-case outage probability represents the maximum outage probability that a class j receiver can experience. In such case, the receiver accesses the system at the latest time instance within the access window, and experiences the poorest channel condition. Therefore, the worst-case outage probability for class j can be expressed as

$$\begin{aligned} P^{w}_{out,j} &= \max_i P^{j,i}_{out} \\ &= \sum_{n=0}^{\lceil K_{d_j}(1+\delta_{d_j})\rceil -1} \binom{N_{max}-I_{cut,j}+1}{n} \\ &\quad (1-h_{j,max})^n \, h_{j,max}^{N_{max}-I_{cut,j}+1-n}, \end{aligned} \tag{6}$$

where $h_{j,max} = \max\left\{h_{j,1},..,h_{j,b_j}\right\}$.

IV. PROPOSED TRANSMISSION SCHEME

We have analyzed the outage probability. In this section, we design a transmission scheme so that outage probability constraints can be satisfied with minimum transmission cost.

A. Outage constraints

For the investigated multicasting system, due to the finite number of transmitted packets, a target PSNR might not be achieved. Nevertheless, a certain level of outage probability, defined as the probability that a target PSNR cannot be satisfied, may be acceptable for wireless networks. Therefore, the QoS can be characterized by average and worst-case outage probability constraints, i.e.,

$$P^{av}_{out,j} \le \epsilon^{av}_{out,j}, \quad j=1,..,J, \tag{7}$$

$$P^{w}_{out,j} \le \epsilon^{w}_{out,j}, \quad j=1,..,J \tag{8}$$

where $\epsilon^{av}_{out,j}$ and $\epsilon^{w}_{out,j}$ denote average and worst-case outage probability constraints, respectively, and $P^{av}_{out,j}$ and $P^{w}_{out,j}$ are given in (5) and (6), respectively.

B. Transmission cost criterion

Transmission capacity in a multicast system is a valuable resource, especially in wireless environments. To efficiently utilize system resources, for asynchronous systems, it is reasonable to minimize the cost in terms of the average number of transmitted packets (including correctly and incorrectly received packets) required for each receiver.

Denote $N_{j,i}$ as the required number of transmitted packets for receiver i in class j, where $i=1,..,M_j$. Among all M_j receivers in class j, assume that there are $M_{j,out}$ receivers which cannot achieve the target PSNR. Without loss of generality, these $M_{j,out}$ receivers are given lower index values than other receivers. The average number of transmitted packets for class j receivers can then be written as

$$\begin{aligned} \bar{N}_j &= \frac{1}{M_j}\sum_{i=1}^{M_j} N_{j,i} \\ &= \frac{1}{M_j}\Big(\sum_{n=1}^{M_{j,out}} N_{j,n} + \sum_{q=M_{j,out}+1}^{M_j} N_{j,q}\Big) \\ &= \frac{M_{j,out}}{M_j}\left(\frac{1}{M_{j,out}}\sum_{n=1}^{M_{j,out}} N_{j,n}\right) \\ &\quad + \frac{M_j - M_{j,out}}{M_j}\left(\frac{1}{M_j - M_{j,out}}\sum_{q=M_{j,out}+1}^{M_j} N_{j,q}\right) \end{aligned} \tag{9}$$

If M_j is moderately large, e.g., $M_j \ge 30$, the fraction of $\frac{M_{j,out}}{M_j}$ can be used to approximate the average outage probability $P^{av}_{out,j}$. Also, by the WLLN, the average numbers inside the brackets in (9) can be approximated by their expected values. Therefore, the expression in (9) can be simplified as follows

$$\bar{N}_j = P^{av}_{out,j} E_n[N_{j,n}] + (1-P^{av}_{out,j}) E_q[N_{j,q}] \tag{10}$$

where n denotes the index of receivers which cannot achieve the target PSNR, and q denotes the index of receivers which can achieve the target PSNR. We next derive these two expected values.

The expected value of $N_{j,n}$ can be obtained by

$$\begin{aligned} E_n[N_{j,n}] &= E_n[N_{max} - I_{j,n}] \\ &= N_{max} - \frac{1}{2} I_{cut,j} \end{aligned} \tag{11}$$

$I_{j,n}$ denotes the initial access time instance for receiver n, which is uniformly distributed over $[1, I_{cut,j}]$.

For receivers with satisfied PSNR, we have

$$E_q[N_{j,q}] = E[N^{j,q}_{C}] + E[N^{j,q}_{INC}] \tag{12}$$

where $N^{j,q}_{C}$ denotes the number of correctly received packets required to decode R_j source bits, and $N^{j,q}_{INC}$ denotes the number of incorrectly received packets before $N^{j,q}_{C}$ packets are successfully collected at the receiver.

Due to the layered packetization structure with $K_1 \le K_2.. \le K_L$, it is obvious that the number of correctly received packets, $N^{j,q}_{C}$ can be expressed as

$$N^{j,q}_{C} = K_{d_j}(1+\delta_{d_j}), \tag{13}$$

where we have removed the integer constraint for convenience.

With a given channel erasure rate, $\rho_{j,q}$, packet transmissions for receiver q can be modeled as independent Bernoulli trials, and as a result, it can be shown that $N^{j,q}_{INC}$ in (12) has a negative Binomial distribution with mean $N^{j,q}_{C}\frac{\rho_{j,q}}{1-\rho_{j,q}}$ [6]. Therefore, Equation (12) can be obtained as

$$\begin{aligned} E_q[N_{j,q}] &= E_{\rho_{j,q}}[E[N^{j,q}_{INC} + N^{j,q}_{C} | \rho_{j,q}]] \\ &= E_{\rho_{j,q}}[N^{j,q}_{C}\frac{\rho_{j,q}}{1-\rho_{j,q}} + N^{j,q}_{C}] \\ &= K_{d_j}(1+\delta_{d_j})\left(1 + \sum_{m=1}^{b_j} p_{j,m}\frac{h_{j,m}}{1-h_{j,m}}\right). \end{aligned} \tag{14}$$

Inserting (11) and (14) into (10), we have

$$\begin{aligned} \bar{N}_j &= (1-P^{av}_{out,j})K_{d_j}(1+\delta_{d_j})\left(1 + \sum_{m=1}^{b_j} p_{j,m}\frac{h_{j,m}}{1-h_{j,m}}\right) \\ &\quad + P^{av}_{out,j}(N_{max} - \frac{1}{2}I_{cut,j}). \end{aligned}$$

The overall transmission cost among all classes, denoted by N_{av}, is defined as

$$N_{av} = \sum_{j=1}^{J} \beta_j \bar{N}_j \tag{15}$$

where $\beta_j > 0$ is a weighting factor set to the fractional significance of class j, and without loss of generality we assume $\sum_{j=1}^{J}\beta_j = 1$.

Authorized licensed use limited to: Queens University. Downloaded on July 05,2010 at 17:03:36 UTC from IEEE Xplore. Restrictions apply.

C. Source bit-allocation problem

With the above discussion on constraints and cost criterion, the allocation scheme can be derived by solving the following constrained optimization problem

$$\min_{K_1,..,K_L} N_{av} \tag{16}$$

subject to

$$P^{av}_{out,j} \leq \epsilon^{av}_{out,j}, \quad j = 1,..,J, \tag{17}$$
$$P^{w}_{out,j} \leq \epsilon^{w}_{out,j}, \quad j = 1,..,J, \tag{18}$$

$$K_1 \leq K_2 ... \leq K_L \tag{19}$$

where N_{av}, $P^{av}_{out,j}$ and $P^{w}_{out,j}$ are given in (15), (5) and (6), respectively.

D. Proposed allocation algorithm

To minimize the cost, we choose the total number of source bits, $\sum_{l=1}^{L} K_l$, as the number of source bits required to satisfy the most demanding target PSNR. Also, it is obvious that setting $d_J = L$ sufficiently utilizes the packetization structure and thus leads to a lower N_{av} in (15).

With the above analysis, we propose an allocation scheme which is a suboptimal solution to (16)-(19). Pseudo code of the proposed allocation scheme is illustrated in Table I.

The idea behind this allocation algorithm can be summarized as follows:

- Let S be the set of all possible allocation schemes.
- For each allocation scheme $s \in S$, the decoding-layer-set is defined as $d_s = [d_{s,1}, .., d_{s,J}]$, where $d_{s,j}$ denotes the required number of successfully decoded layers needed to satisfy class j's QoS with zero outage, where $j = 1, .., J$, and $d_{s,i} \leq d_{s,j}$ for $i < j$.
- All the allocation schemes in S are then grouped into different subsets such that all the allocation schemes in a subset have the same values for the decoding-layer-set. The decoding-layer-set for subset g, where g denotes the subset index, is denoted by d^g.
- For each subset g, we choose the allocation scheme which equally (or approximately equally) allocates $R_j - R_{j-1}$ source bits from layers $d_{j-1} + 1$ to d_j. This allocation scheme and its corresponding cost are denoted by $\mathbf{k}_{opt,g}$ and C_g, respectively. The set is feasible if and only if the outage probability constraint can be satisfied.
- Minimization is accomplished by checking the cost C_g for each feasible subset.

V. SIMULATION

A. Outage probability

Before deriving the allocation schemes, in this section, we numerically illustrate the outage probabilities (5)-(6) for class j as a function of K_{d_j}, as shown in Figure 2. For simplicity, we assume the channel erasure rate to be the same for all class j receivers, denoted by h_j.

Note that Figure 2 can be applied to any class. An allocation scheme is feasible if and only if the outage probability constraints for all classes can be satisfied. For example, assume there are two classes of receivers, and the channel erasure rates for these two classes are 0.01 and 0.2, respectively. With average outage probability constraints of 10^{-5} for class 1, and 10^{-2} for class 2, from Figure 2, we can show that a feasible allocation scheme must satisfy $K_{d_1} \leq 935$ and $K_{d_2} \leq 755$.

TABLE I
PSEUDO CODE FOR THE PROPOSED ALLOCATION SCHEME.

```
Initialization: Best= 10000, $d_0 = 0$; $R_0 = 0$;
Derive source bit rate $R_j$, $j = 1, .., J$, from (1);
Foreach $d_1 = 1 : 1 : L$
    ....
    Foreach $d_{J-1} = d_{J-2} : 1 : L$
        Allocate $R_j - R_{j-1}$ bits equally, or approximately
        equally among $d_j - d_{j-1}$ layers. Get $k_1, .., k_L$.
        If $d_m = .. = d_n$, where $1 \leq m \leq n \leq L$
          Re-allocate $R_n - R_{m-1}$ bits equally
          among $d_n - d_{m-1}$ layers. Get $k_1, .., k_L$.
        End;
        If $k_1 \leq k_2 .. \leq k_L$ and outage constraints
        (17) and (18) are satisfied:
          Derive Cost according to (15);
          If Cost $\leq$ Best
            Best = Cost;
            Optimal allocation scheme is set to
            $\mathbf{k}_{opt} = [k_1, .., k_L]$;
          End;
        End;
    End foreach $d_{J-1}$
    ....
End foreach $d_1$
```

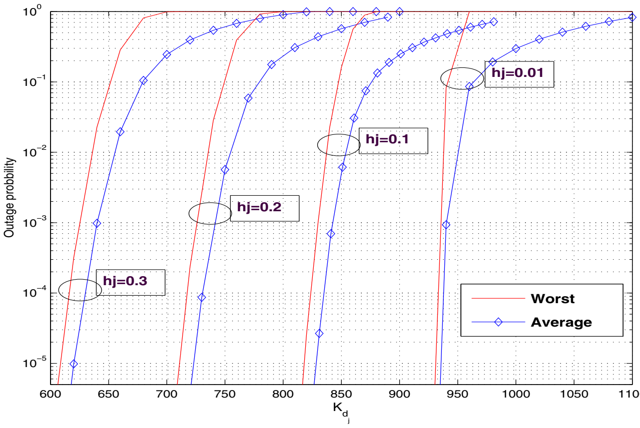

Fig. 2. Average and worst-case outage probability for different values of channel erasure rates and allocation schemes (represented by K_{d_j}). The cutoff deadline and access window are set to $N_{max} = 1200$ and $[1, 200]$, respectively.

B. Allocation schemes

Now we illustrate how to allocate source bits to packets. Consider a single cell multicasting system with two classes of receivers. The target PSNR for class 1 and class 2 are $\gamma_1 = 27$ dB and $\gamma_2 = 30$ dB, respectively. A standard 512×512 Lenna image is used as a vehicle for testing the proposed scheme. The image is compressed with the set partitioning in hierarchical trees (SPIHT) algorithm [7] at a rate of 0.2 bits/pixel. From the operational rate-distortion curve, the minimum number of the source bits needed to provide the above PSNR targets are $R_1 = 11072$ and $R_2 = 24728$, respectively. The packet size is $L = 47$.

The maximum number of transmitted packets is set to $N_{max} = 1200$, and the arrival windows for class 1 and class 2 receivers are set to $[1, 300]$ and $[1, 200]$, respectively, unless specified otherwise. For the proposed UEP scheme, a rateless code with a typical average overhead rate of 0.05 [8] is employed.

As described previously, source bits should be allocated

Authorized licensed use limited to: Queens University. Downloaded on July 05,2010 at 17:03:36 UTC from IEEE Xplore. Restrictions apply.

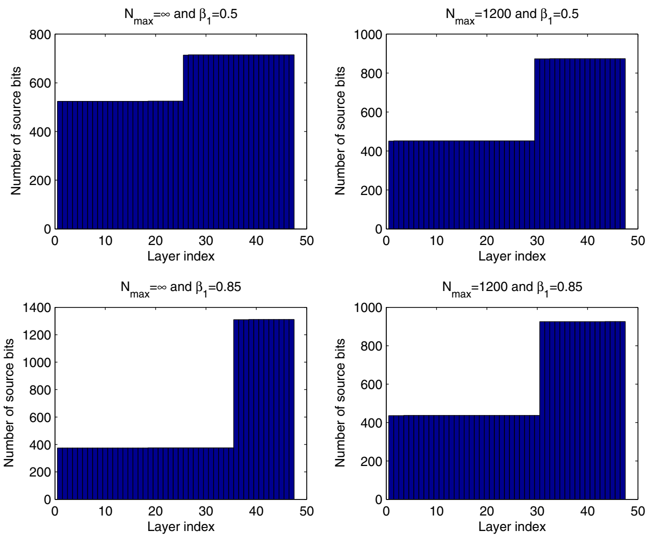

Fig. 3. Allocation of source bits over $L = 47$ layers for systems with (right) and without (left) cutoff deadline. The channel erasure rates are set to $h_1 = 0.4$ and $h_2 = 0.01$ for class 1 and 2, respectively. The outage probability constraints are as follows: $\epsilon^{av}_{out,1} = 10^{-6}$, $\epsilon^{av}_{out,2} = 10^{-2}$, $\epsilon^{w}_{out,1} = 10^{-2}$ and $\epsilon^{w}_{out,2} = 1$. Note that the subplots have different vertical scales.

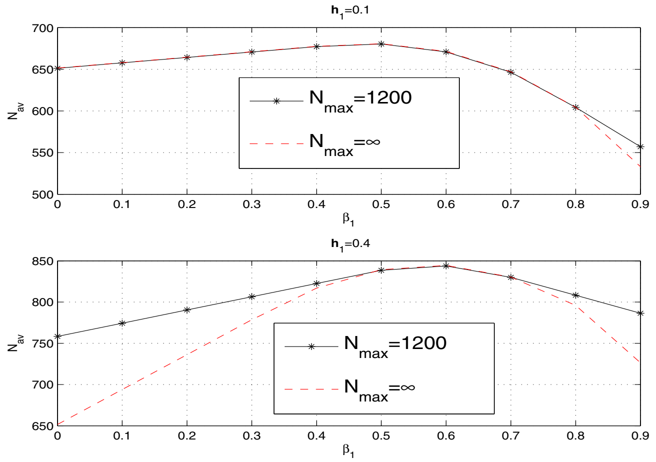

Fig. 4. Cost comparison between the systems with and without cutoff deadline. Different values of channel erasure rate for class 1, denoted by h_1, are tested, and the channel erasure rate for class 2 is $h_2 = 0.01$. The access windows for both classes are $[1, 200]$. The average outage probability constraints are set to $\epsilon^{av}_{out,1} = 10^{-4}$ and $\epsilon^{av}_{out,2} = 10^{-6}$, respectively. No worst-case outage probability constraints are imposed for both classes, i.e., $\epsilon^{w}_{out,1} = \epsilon^{w}_{out,2} = 1$.

to the layers appropriately to satisfy the outage probability constraints with least system transmission cost. Figure 3 presents the bit allocation produced by the algorithm in Table I. For comparison, we also present the allocation for the case of no cutoff limit, i.e., $N_{max} = \infty$.

With $N_{max} = \infty$, if the weighting factor of class 1 is not dominant, e.g., $\beta_1 \leq 0.5$, the allocation algorithm needs to spread the source bits required by class 1 over as few layers as possible, so that more layers can be devoted to the source bits required by class 2 and as a result, a smaller overall cost can be achieved. This allocation, however, is not feasible for a cutoff deadline of $N_{max} = 1200$, due to violating the outage probability constraint for class 1. In such case, as presented in Figure 3, the source bits required by class 1 should be spread over more layers to reduce K_{d_1}, so that the outage constraint for class 1 can be satisfied. Doing so, however, leads to an increased K_{d_2}, due to the fewer layers left for the extra source bits required by class 2.

Similarly, for systems with $N_{max} = \infty$, if class 1 is made more significant, e.g., $\beta_1 = 0.85$, the bits required for class 1 should be spread over more layers to achieve a smaller cost for class 1. This allocation, however, leads to a larger K_{d_2}, which violates the outage probability constraint for class 2 when the maximum number of transmitted packets is set to $N_{max} = 1200$. In such case, the source bits required by class 1 should be spread over fewer layers in order to make room for class 2, so that the outage probability constraint for class 2 can be satisfied.

C. Performance of the proposed allocation schemes

In this section, we assess above derived allocation schemes in terms of the overall transmission cost. From Figure 4, it can be observed that if the channel erasure rate is small, e.g., $h_1 \leq 0.1$, there is no obvious loss by imposing the cutoff deadline. This is because the bit allocation derived with $N_{max} = \infty$ is also a feasible solution to the system with $N_{max} = 1200$. When the channel erasure rate is larger, however, the cost is increased for systems with a finite cutoff deadline, especially for cases where one particular class dominates, e.g., $\beta_1 \geq 0.7$, or $\beta_1 \leq 0.4$. This is the case because for systems with $N_{max} = \infty$, if one particular class dominates, the dominated class can absorb a larger K_{d_j} without violating any outage constraint. For systems with finite cutoff deadline, K_{d_j} for the dominated class is limited by the outage probability constraint, leading to an increase in overall transmission cost.

VI. CONCLUSIONS

In this paper, a multimedia multicasting system is investigated which employs rateless codes and a PET-like layered packetization structure. A closed-form outage probability is derived for the investigated layered multicast. We then propose a novel transmission scheme which aims to adapt to the channel conditions, and trade off the transmission costs among heterogeneous receivers, so that the overall system transmission cost can be minimized subject to outage probability constraints. Simulation results show that the proposed scheme performs well for QoS-aware multicast systems which have real-time delay constraints and asynchronous multicast start time instances, and as a result, can be applied to a variety of emerging multicasting applications, such as Internet Protocol television and wireless video on demand.

REFERENCES

[1] A. Albanese, J. Blomer, J. Edmonds, M. Luby and M. Sudan, "Priority encoding tranmision", *IEEE Trans. Inform. Theory*, vol. 42, pp. 1737-1744, Nov. 1996.

[2] R. Prasad and M. Ruggieri, "Technology Trends in Wireless Communications", Artech House Publishers, 2003.

[3] N. Rahnavard, B. N. Vellambi and F. Fekri, "Rateless codes with unequal error protection property", *IEEE Tran. on Information Theory* , vol. 53, no. 4, pp. 1521-1532, April 2007.

[4] D. Vukobratovic, V. Stankovic, D. Sejdinovic, L. Stankovic and Z. Xiong, "Expanding window fountain codes for scalable video multicast", *Proc. IEEE ICME 2008*, pp. 77-80, June 2008.

[5] W. Sheng, S. D. Blostein, W. Y. Chan and Y. Cao, "Asynchronous and Reliable Multimedia Multicast with Heterogeneous QoS Constraints", *Proc. IEEE ICC 2010 (in press)*.

[6] M. Abramowitz and I. A. Stegun, *Handbook of mathemetical functions*, Dover publications, 1972.

[7] A. Said and W. A. Pearlman, "A new, fast, and efficient image codec based on set partitioning in hierarchical trees", *IEEE Tran. on Circuits and Systems for Video Technology*, vol. 6, pp. 243-250, June 1996.

[8] J. W. Byers, M. Luby and M. Mitzenmacher, "A digital fountain approach to asynchronous reliable multicast", *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 8, pp. 1528-1540, October 2002.

Authorized licensed use limited to: Queens University. Downloaded on July 05,2010 at 17:03:36 UTC from IEEE Xplore. Restrictions apply.